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Algorithm for Evolutionary Optimization of Reinforced Concrete Frames Subject to Nonlinear Material Deformation

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Abstract

The authors designed an evolutionary procedure for the optimal design of reinforced concrete structures of flat frames manufactured without reinforcement pre stress. The aim of the research is to minimize the planned production cost of the frame with restrictions on strength, hardness and crack resistance. The physically nonlinear behavior of concrete and armature, as well as the possibility of crack formation in cracked concrete is taken into consideration. The search is performed on discrete sets of design parameters: the size of the cross sections of bars, number and diameter of rebars, concrete and reinforcement grades. A genetic algorithm, providing for parallel operation of two populations is formed. Within the main population specimen are exposed to crossing over operations, mutation and selection on the basis of production cost criteria. We also introduce the auxiliary population, used to save the best specimen and provide an iterative process, if necessary, with an elite genetic material. The bulk population is divided into two sub-objects. If any of the objects of the first sub-group is not satisfied with at least one of the active constraints, it is replaced by a supporting population object which is not used in the general population or by a newly formed variant of this carrier system. If the restrictions are not met for the object of the second sub-group, then a fine for the value of its objective function is introduced. Such an approach provides a sufficiently rapid convergence of iterations, which is essential in a fair time-consuming calculation of a structure options in a nonlinear setting. The efficiency of the proposed method is illustrated by the example of a single-span reinforced concrete frame optimization.

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Keywords: Evolutionary optimization; genetic algorithm; reinforced concrete frame; production cost; strength; hardness; crack resistance

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1. Introduction

One of the most effective approaches to the solution of complex optimization problems are evolutionary computational schemes. The methods of this type include genetic algorithms [1], bat-inspired algorithm [2], simulated annealing algorithm [3], ant colony optimization [4], particle swarm optimizer [5], harmony search algorithm [6], big bang- big crunch algorithm [7] and others. Several papers dealt with issues of optimization using evolutionary algorithms of building systems [8-16]. At the same time the problem of the creation of efficient procedures to optimize the construction of load-bearing structures, for which it is necessary to perform the calculation of the stress-strain state in the nonlinear setting, still requires a further research. In this article we consider such an issue associated with the search of optimal design solutions for flat solid-cast reinforced-concrete frames, manufactured without reinforcement stress.

The optimal search is based on a three-level iterative scheme, including the procedure of the genetic algorithm and the intercept method implementing an account of nonlinear behavior of the bearing system. Physics of nonlinear behavior of concrete and reinforcement, including the possibility of crack formation in cracked concrete are taken into consideration.

2. Problem statement

Suppose the flat reinforced concrete frame, manufactured without reinforcement stress is formed by **collar beams** and columns of a rectangular cross section. We believe that the width b (Fig. 1a) for all the rods of the frame is the same. For all the elements of the design we provide the introduction of two rows of reinforcement. We minimize the planned production cost C_b of the frame:

$$C_b\left(b,\ h_i,\ (d_t,\ n_t),\ K_b,\ K_S\right) \to \min\ ,$$

where h_i is the height of the cross section of i-sector or i-group of sectors of frame rods (i=1,…, i_0), i_0 is the number of independently varying heights, (d_t, n_t) is the pair of numbers defining the diameter and the number of bars for the independently varying layer t or a group of reinforcement layers (t=1,…, t_0), t_0 is the number of such pairs, K_b , K_S are concrete and reinforcement grades for the frame.

We considered the production cost of concrete mix, and all kinds of steel used in the production of reinforcement and embedded items; the total cost of reinforcement production (reinforcement cage, separate rods, mounting loops); the production cost of embedded parts, the placement of reinforcement and embedded items into the form, molding of products; costs of operation and maintenance of the form; the production cost of steam used for the product thermal treatment [17].

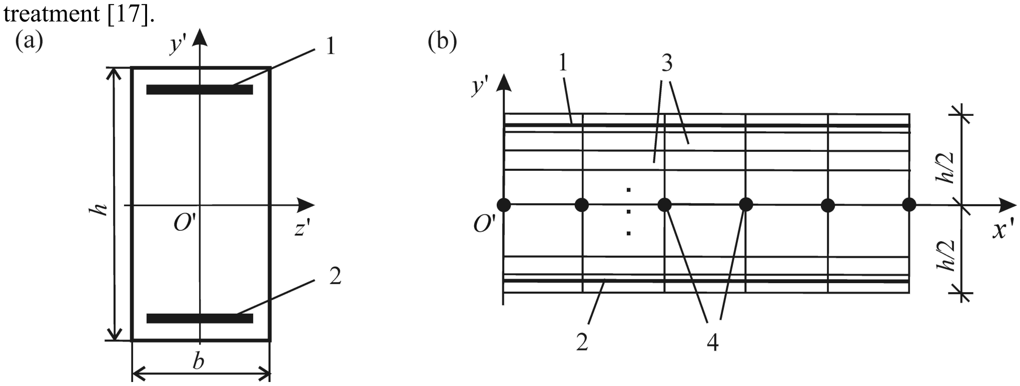

Fig. 1. (a) Cross section of the collar beam and the column; (b) scheme of the finite element model: 1, 2 are layers of reinforcement; 3 are layers of concrete; 4 are nodes of multilayer finite elements.

The weight of the longitudinal principal reinforcement M_{Sw} is directly dependent on variable parameters $(d_t,\ n_t)$. The weight of embedded items can be calculated approximately according to the length of the collar beams and the columns. [17] The mass of the transverse reinforcement M_{ST} can be expressed through the mass of the longitudinal reinforcement:

$$M_{ST} = \theta_{ST} M_{Sw},$$

where θ_{ST} is the transverse reinforcement ratio.

The following limitations should be considered [18, 19]:

1) *Strength requirements*:

$$\forall \sigma_b < 0: \left|\sigma_b\right| \le \tilde{R}_b = \gamma_{bi} R_b;\ \forall \sigma_S > 0: \sigma_S \le \tilde{R}_S = \gamma_{Si} R_S;\ \forall \sigma_S < 0: \left|\sigma_S\right| \le \tilde{R}_{Sc} = \gamma_{Si} R_{Sc},$$

where σ_b, σ_S are normal stresses in concrete and reinforcement, R_b is the calculated resistance of concrete in case of axial compression, R_S, R_{Sc} are calculated resistance of concrete and reinforcement in case of stretching and compression, γ_{bi}, γ_{Si} are condition load effect factor of concrete and reinforcement.

2) *Requirement for harshness*:

$$\frac{f}{f_{ult}} - 1 \le 0,$$

where f is the vertical or horizontal movement, f_{ult} is the limit value of such a displacement.

3) *Conditions for opening width of transverse cracks:*

$$\frac{a_{crc}}{a_{crc,ult}} - 1 \le 0,$$

where a_{crc} is the opening width of transverse cracks in concrete, $a_{crc,ult}$ – maximum permissible width of cracks in concrete which depends on load duration.

4) *Lack of inclined cracks' condition.*

5) *Frame stability insurance.*

6) *Local structural strength provision.*

3. Search algorithm

We believe that the data on the geometry of the median lines of collar beams and columns, loads, connections, material characteristics, acceptable values of the parameters are included into the source data. We form a three-level iterative process. The external cycle is performed to re-determine the coefficient θ_{ST} on the basis of the condition for the implementation of the restrictions 4 and 6. Initially, its value is defined by design reasons, then - adjusted according to the calculation results. Average cycle performs evolutionary search, which takes into account the limitations 1-3. The internal cycle of the method of variable elasticity parameters implies a solution of the nonlinear problem for each of the options considered in the population of the carrier system (the project). The limitation 5 is checked for the variant of the construction obtained as a result of an optimal search. Each project is interpreted as an object with a certain set of parameters [1].

The discrete set of possible values of the parameters are arranged from the smallest to the largest: in ascending order of the sizes of b, h_i, of cross-sectional areas of reinforcement layers, increasing concrete and reinforcement grades. We use the approaches to the construction of a mixed strategy of genetic algorithm proposed in [20]. We take into account the major group of the projects Π_Λ having a fixed even number of n objects and an auxiliary group of improved objects Π_Ω, the size of which depends on the results of the evolutionary algorithm, but does not exceed n .When choosing the initial group of projects Π_Λ, n of identical construction options having the largest allowable parameter values is formed. Each step of the genetic algorithm includes the following stages:

1) *The verification of the restrictions for a group of objects* Π_Λ *on the basis of the iterative process of solving a nonlinear problem is performed.* We perform the calculation of the stress-strain state of the construction options of the given group. The group Π_Λ is divided into sub-groups Π_1 and Π_2 of the objects. If any of the subgroups of projects is not satisfied with at least one of the limitations of 1-3, it is replaced by the project from Π_Ω group, which is not used in the group Π_Λ or by a newly formed option of the carrier system. If the restrictions are not met for the object from the group Π_2 the penalty, which increases the value of the objective function is introduced.

2) *Editing of the group* Π_Ω *of improved projects.* Each of the objects in the group is checked according to two criteria: whether an object exists in the group Π_Ω , value of the object C_b is greater than the value of the objective function in this group. If both responses are negative, the object is placed in the group Π_Ω. If the number of objects in the sub-group exceeds n, the project with the highest value of C_b is excluded from it.

3) *Mutation*. Randomly several parameters can be changed for a part of projects of the Π_Λ group. We introduce the following scheme of the selection of parameters. With the help of a random number generator, which operates in the interval (0, 1) and having a uniform distribution law, we find the value m_a that is compared with the controlling number of the mutation m. If the inequality $m_a>m$ is observed, then randomly with equal probability any of the acceptable parameters is selected. Otherwise the number of the current position of the parameter in the set of its admissible values may increase or decrease by 1-2 units**.**

4) *Selection and crossing over.* From the group of the objects Π_Λ, we have chosen $n/2$ pairs of circuit design options with stochastic displacement (roulette method) [1] according to the value of C_b and implemented the procedure of a single-point crossover.

The external cycle usually converges in one or two iterations. The internal one requires not more than 80-120 iterations to satisfy the restrictions 1-3. The convergence of the evolutionary algorithm was almost achieved for 100-400 iterations.

When forming the finite element model, collar beams and columns are separated into thin layers of concrete and reinforcement (Fig. 2b). It is believed that each of the layers works in stretching and compression. It is assumed that for set of layers the hypothesis of plane sections is true. We obtained dependences for strain, elasticity and stiffness matrices of finite elements of concrete and reinforcement layers. We considered the influence of longitudinal forces on bending using geometric matrices of finite elements [21]. Stretching-compression diagrams of concrete and reinforcing steel were made in accordance with [18]. In the first iteration the object is calculated on the basis of the initial modules of concrete and reinforcement elasticity at zero geometric matrix. In subsequent iterations we considered secant modulus, determined on the basis of the deformation diagrams.

In each iteration $s>1$ the following system of linear algebraic equations is solved:

$$\left(\left[K\left(E_{bi(s-1)},E_{Si(s-1)}\right)\right]^{(s)}+\left[K_G\left(N_{i(s-1)}\right)\right]^{(s)}\right)\{\delta\}^{(s)}=\{R\},$$

where $[K]^{(s)}$ is the stiffness matrix of the finite element model for the iteration s, obtained by taking into account the secant modulus of elasticity of concrete and reinforcement $E_{bi(s\text{-}1)}$, $E_{Si(s\text{-}1)}$, which are determined for every finite element of the layer i in accordance with the iteration results s-1, $[K_G]^{(s)}$ is the geometric matrix of the finite element system of the iteration s, expressed in terms of the longitudinal forces $N_{i(s\text{-}1)}$ of finite elements of layers for the iteration s-1, $\{\delta\}^{(s)}$ is the vector of nodal displacements obtained in iteration s, $\{R\}$ is the vector given to the external load nodes.

The algorithm is implemented in the software package BGITAFEM/OPTIMA [22].

4. Optimization example

We carried out the optimization process of solid-cast reinforced concrete frame shown in Fig. 2. The action of the short-term loads q_1, q_2 on the frame as well as gravity forces q_{GA}, q_{GB}, q_{GC} recalculated into the process of optimization were considered. When four runs were made on the count, the solution was the same. Admissible and obtained design values are given in Table 1, where h_A, h_B, h_C are the heights of the cross sections of the bars *A*, *B*, *C*. For this example, it was required to perform one iteration of the external cycle and 132-346 genetic algorithm iterations. The implementation of the calculation until the completion of the 346th iteration of the genetic algorithm took PC Intel Pentium Processor T4300 (2,10 GHz, 800 MHz FSB) took less than half an hour.

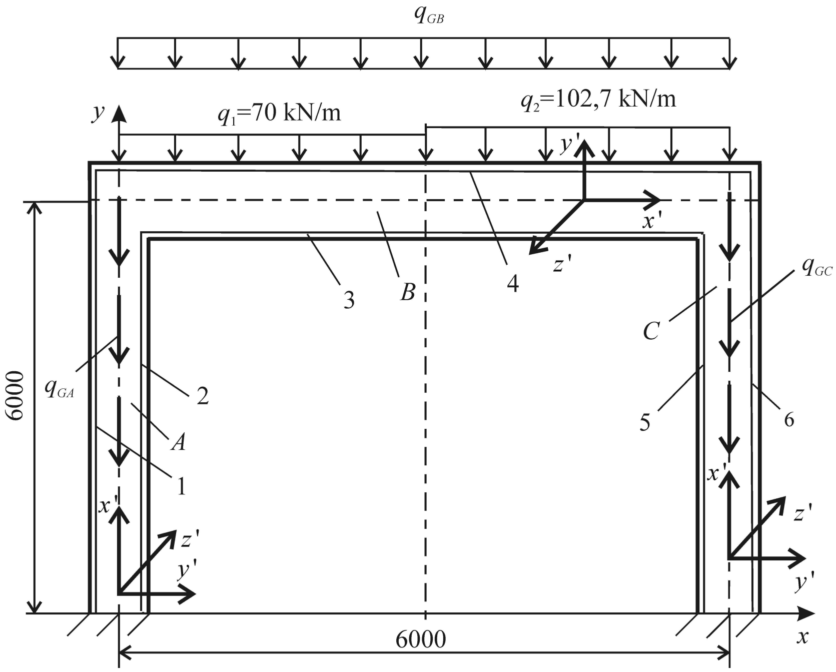

Fig. 2. Reinforced concrete frame: *A*, *C* are the columns; *B* is the collar beam; 1-6 are the numbers of reinforcement layers.

Table 1. Variable parameters and the results of the frame optimization

Number of parameter	Parameter, dimensions	Admissible values	Optimization result
1	*b*, cm	20; 22; 25; 30; 32; 35	20
2	h_A, cm	25; 30; 35; 40; 45; 50; 55; 60; 65	40
3	h_B, cm	25; 30; 35; 40; 45; 50; 55; 60; 65	60
4	h_C, см	25; 30; 35; 40; 45; 50; 55; 60; 65	60
5	$(d_1,\ n_1)$, (mm, ps)	(20, 4); (25, 3); (18, 6); (20, 5); (32, 2); (28, 3); (22, 5); (25, 4)	(32,2)
6	$(d_2,\ n_2)$, (mm, ps)	(12, 5); (12, 6); (14, 5); (16, 4); (14, 6); (18, 4); (22, 3); (16, 6)	(12, 5)
7	$(d_3,\ n_3)$, (mm, ps)	(12, 5); (12, 6); (14, 5); (16, 4); (14, 6); (18, 4); (22, 3); (16, 6)	(12, 6)
8	$(d_4,\ n_4)$, (mm, ps)	(12, 5); (12, 6); (14, 5); (16, 4); (14, 6); (18, 4); (22, 3); (16, 6)	(16, 6)
9	$(d_5,\ n_5)$, (mm, ps)	(12, 5); (12, 6); (14, 5); (16, 4); (14, 6); (18, 4); (22, 3); (16, 6)	(12, 5)
10	$(d_6,\ n_6)$, (mm, ps)	(12, 5); (12, 6); (14, 5); (16, 4); (14, 6); (18, 4); (22, 3); (16, 6)	(12, 5)
11	Concrete grade	B15; B20; B25; B30; B35; B40	B20
12	Reinforcement grade	A300; A400; A500; A600	A400

5. Conclusion

We have worked out the algorithm of the optimization of framed reinforced concrete structures made without preliminary reinforcement stress, using evolutionary modeling. The planned production cost of the object is considered to be an objective function. The dimensions of the cross-sections of collar beams and columns, the number and diameter of the longitudinal reinforcement bars, concrete and reinforcement grades vary. The search is performed on discrete sets of parameters that correspond to the practice of real design of reinforced concrete systems. For example, optimization of a single-span frame illustrated sufficiently high stability and speed of convergence of the presented computational scheme. The proposed algorithm can be used in the Computer-Aided Design systems of building structures.

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